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Faraday Rotation of EY-1 Glass

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13. ABSTRACT

EY-1 is a terbium-silicate glass recently developed by Owens-Illinois. It offers great potential as a Faraday rotator-isolator in high power laser systems because of its high Verdet constant, $V = -4.06 \pm 0.1 \times 10^{-2}$ min/Oe-cm at 1.064 μ. This allows one to use shorter lengths of glass and lower magnetic fields than with other rotator glasses. We have measured V in this glass at 1.06 μ with fields up to 60 kOe and, in addition, the change in V with temperature and wavelength:

$$\left(\frac{\partial V}{\partial T}\right)_{1.064\ \mu} = -2.2 \pm 0.4 \times 10^{-4} \text{ min/Oe-cm}^\circ\text{C}$$

$$\left(\frac{\partial V}{\partial \lambda}\right)_{12^\circ\text{C}} = 1.1 \pm 0.2 \times 10^{-5} \text{ min/Oe-cm-cm}^{-1}.$$

The requirements that these numbers impose on the field, temperature and wavelength stability and uniformity are discussed.

14 KEY WORDS	LINK A		LINK B		LINK C	
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Faraday rotator						
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AUTHORIZATION

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I. INTRODUCTION

Faraday rotators are used in laser plasma experiments to isolate the laser from light back-reflected from the target. These back-reflections are especially serious in large multistage laser systems because low reflected light intensities can be amplified to destructive levels by propagating backwards through the amplifying chain. The use of Faraday rotators and polarizing optical elements offers one method of preventing this destructive feedback. This paper considers some design concepts concerning Faraday rotators for laser systems and presents measurements made on Owens-Illinois EY-1 Faraday rotator glass.

II. DESIGN CONCEPTS

The design of a Faraday rotator system for a high power laser ($>10^{12}$ W) is governed by the diameter of the laser beam and the length of the Faraday rotator material. The length is determined by the self-focusing length of the material at the desired laser power density. The Verdet constant and the length determine the necessary magnetic field strength.

Glasses are presently used as the Faraday rotator material in high power laser systems. Recently Owens-Illinois has developed for commercial sale a terbium-silicate base glass, EY-1, that has a Verdet constant of about -4×10^{-2} min/Oe-cm. It is a paramagnetic glass. A similar glass composition was first formulated for Faraday rotator purposes by Robinson and Graf.(1) For comparison(2,3), at 1.06 μ, Schott SF-6 lead-silicate glass has a Verdet constant of $+ 1.9 \times 10^{-2}$ min/Oe-cm and a common soda lime silicate glass has a Verdet constant of $+ 0.65 \times 10^{-2}$ min/Oe-cm. These last two glasses are both diamagnetic. The high Verdet constant of EY-1 allows a shorter length of material to be used for a given field. This reduces the energy in the magnetic field and increases the self-focusing damage threshold.(4) The base glass is similar to the Owens-Illinois laser glass ED-2 and consequently it should exhibit desirable surface and bulk damage characteristics.

III. EY-1 GLASS MEASUREMENTS

We have measured the following properties of EY-1 glass:

(1) Verdet constant V up to 60 kG at 1.06 μ and 19°C.

(2) $\left(\frac{\partial V}{\partial T}\right)_\lambda$ change in V with temperature at constant wavelength at 30 kG

(3) $\left(\frac{\partial V}{\partial \lambda}\right)_T$ change in V with wavelength at constant temperature at 30 kG.

These numbers determine the field strength of the system and the temperature and wavelength stability required to maintain a given extinction ratio with crossed polarizers.

The experimental arrangement is shown in Fig. 1. The Verdet constant was measured by noting the change in rotation with magnetic field $\theta = V\ell H$[5]. θ is traditionally measured in minutes, ℓ in cm, H in Oe, and V, consequently, in min/Oe-cm. The magnetic field was provided by the NRL magnet facility and was constant to ±1% over the sample volume (1.0 cm dia x 3.9 cm long). The rotation was detected by measuring the null in transmitted light through Glan-Thompson prisms with a photomultiplier detector. The extinction ratio was 100:1, and the angular error was ± 20 min. The temperature was monitored with an iron-constantan thermocouple that was thermally attached to the glass surface with silicone grease. The reference junction was held at a constant temperature in ice water, and the overall temperature was held to ±1°C during the constant temperature experiments.

A Chromatix Model 1000C Nd:YAℓG laser was used as the light source. The wavelength was varied by adjusting the wavelength selector prism on the laser to the different Nd^{3+} laser transitions, and the laser was operated at about 10 pps in a pulsed mode. No attempt was made to synchronously detect the pulses or to use boxcar integration techniques because the accuracy of the experiments was sufficient for Faraday rotator design purposes.

III-1. Verdet-Constant vs Field Strength

Figure 2 shows the rotation as function of field strength. The Verdet constant at 1.064 μ and 19°C is $V = -4.06 \pm 0.1 \times 10^{-2}$ min/Oe-cm. This is lower than the value quoted in Ref. (1) because of the lower Tb content[6].

III-2. Verdet Constant vs Wavelength

Figure 3 shows the variation in the Verdet constant with wavelength. The field was held constant at 30 kOe ± 1% and the temperature was held at 12°C to ± 0.2°C. The laser was tuned over the available frequencies from 0.946 μ to 1.079 μ, and the change in rotation was determined. The change in Verdet constant is:

$$\left.\frac{\partial V}{\partial \lambda}\right|_{T = 12°C} = 1.1 \pm 0.2 \times 10^{-5} \text{ min/Oe-cm-cm}^{-1}.$$

The rotation increases with frequency and the variation per cm^{-1} is about 10^{-3} x Verdet constant at 1.06 μ.

III-3. Verdet Constant vs Temperature

Figure 4 shows the variation in the Verdet constant with temperature[6,7]. This measurement is the least accurate of those made. The sample was heated with hot air and allowed to cool to the equilibrium magnet temperature. During the cooling period the temperature was found to be reasonably uniform in the sample by changing the direction of hot air flow and remeasuring $\frac{\partial V}{\partial T}$. Also the rate of cooling to the plexiglass holder was slower than the calculated rate of thermal equilibrium in the glass itself (~ 5 sec), which indicates that a reasonably flat temperature profile existed across the sample. The measurements at the highest temperature are less accurate as they were taken under the most non-uniform heat distributions in the sample. The value is:

$$\left(\frac{\partial V}{\partial T}\right)_{\lambda = 1.064} = -2.2 \pm 0.4 \times 10^{-4} \text{ min/Oe-cm-°C.}$$

This value per degree Kelvin is about 10^{-2} x Verdet constant at 1.06 μ.

The Faraday rotation by a paramagnetic material as a function of field and temperature is given by[5,7]:

$$\begin{aligned} \theta &= A\ell \tanh(\mu_e H/kT) + BH \\ &\cong c\,\ell H/T \text{ for } \frac{\mu_e H}{kT} << 1 \end{aligned} \qquad (1)$$

where $\frac{c}{T}$ = Verdet constant at the specified wavelength λ, μ_e is magnetic moment in Bohr Magnetons, H is field in Oe, k is Boltzman's constant, ℓ is the sample length, and A is a constant. B is a temperature independent term which is usually found to be negligible[7]. It will not be considered further here. Thus

$$\frac{d\left(\frac{\theta}{\ell H}\right)}{dT} = \frac{dV}{dT} = -\frac{c}{T^2} = -\frac{V}{T} \qquad (2)$$

which in our case for T = 12°C, yields:

$$\frac{dV}{dT} = -1.4 \times 10^{-4} \text{ min/Oe-cm-°C.}$$

This is less than the measured value, and outside of the experimental error limits. A systematic error may be due to the fact the center of the glass rod is slightly higher in temperature than the edge where the temperature was monitored. This is caused by the cylindrically symmetric temperature profile of a cooling thin cylinder. This however would not reduce the value by more than 20 - 30%. We use the experimental value which is higher than the theoretical value. The measured value allows one to calculate the required temperature uniformity conditions in a Faraday rotator system.

IV. EXTINCTION RATIO VS CHANGE IN VERDET CONSTANT[3,8,9]

For transmission of unpolarized light through crossed polarizers, which we assume is the normal operating condition of the Faraday rotator, the following equation is obtained[3] (see Fig. 5):

$$I_T = \tfrac{1}{2} I_o \sin^2(\theta - \pi/4) \tag{3}$$

in which $\theta = \theta(y)$ where y can be field, temperature, or wavelength, and θ is defined such that $I_T = 0$ at $\theta = \pi/4$. The rotation of the direction of polarization by the glass is nominally set to be 45°, but variation in the rotation with temperature and wavelength may occur. To determine the effect of these variations we note that:

for $\theta = \pi/4 + \Delta\theta$

$$\sin^2(\theta - \pi/4) \simeq \Delta\theta^2$$

$$\Delta\theta = \frac{\partial\theta}{\partial y}\Delta y \quad (\Delta\theta \text{ measured in radians}) \tag{4}$$

then $I_T \simeq \tfrac{1}{2} I_o \left(\frac{\partial\theta}{\partial y}\Delta y\right)^2$

$$\frac{I_T}{I_o} = \tfrac{1}{2}\left(\frac{\partial\theta}{\theta y}\Delta y\right)^2 = \text{Extinction Ratio} = E. \tag{5}$$

Using the relation $\theta = \ell HV$ where

$$\frac{\partial\theta}{\partial y} = \ell H \frac{\partial V}{\partial y}$$

then

$$\frac{I_T}{I_o} = \tfrac{1}{2}\left(\frac{\theta}{V}\frac{\partial V}{\partial y}\Delta y\right)^2 \tag{6}$$

(1) Transmission vs change in temperature ($y = T$ °K) using equation (6) and the measured values for V and $\frac{\partial V}{\partial T}$, ($\theta = 45°$):

$$\frac{\theta}{V} = \frac{2700}{.04} = 6.74 \times 10^4 \text{ Oe-cm}$$

$$\frac{\partial V}{\partial T} = -2.2 \times 10^{-4} \text{ min/Oe-cm-°C} = -6.5 \times 10^{-8} \text{ rad/Oe-cm-°C}$$

$$\frac{I_T}{I_o} = 0.96 \times 10^{-5} (\Delta T)^2, \ \Delta T \text{ in °C.}$$

To maintain an extinction ratio of $< 10^{-4}$, one must hold the temperature to ± 1.5°C.

(2) Transmission vs change in wavelength ($y = \lambda$ cm^{-1}) using equation (6) and the measured values for V and $\frac{\partial V}{\partial \lambda}$:

$$\frac{\theta}{V} = 6.74 \times 10^4 \text{ Oe-cm}$$

$$\frac{\partial V}{\partial \lambda} = 1.1 \pm 0.2 \times 10^{-5} \text{ min/Oe-cm-cm}^{-1}$$

$$= 3.3 \times 10^{-9} \text{ rad/Oe-cm-cm}^{-1}$$

$$\frac{I_T}{I_o} = 2.45 \times 10^{-8} (\Delta\lambda)^2, \quad \Delta\lambda \text{ in cm}^{-1}.$$

In Nd^{3+} glass, where $\Delta\lambda \simeq 100$ cm^{-1}, $\frac{I_T}{I_o} \simeq 2 \times 10^{-4}$. This extinction ratio is tolerable in a large Nd glass system.

(3) Transmission vs change in magnetic field ($y = H$ in Oe). From equation (5):

$$E = \frac{I_T}{I_o} = \frac{1}{2}\left(\frac{\partial \theta}{\partial H} \Delta H\right)^2$$

using

$$\frac{\partial\theta}{\partial H} = \ell V, \qquad \text{then}$$

$$E = \tfrac{1}{2}\, \ell^2 V^2\, \Delta H^2$$

or

$$\Delta H = \frac{\sqrt{2E}}{\ell V} \; .$$

Using

$$H = \frac{\theta}{\ell V}$$

$$\frac{\Delta H}{H} = \frac{\sqrt{2E}}{\theta} \; .$$

For an extinction ratio E of 10^{-4}, and $\theta = 45° = .79$ rad.

$$\frac{\Delta H}{H} = 1.8 \times 10^{-2} = 1.8\% \; .$$

The magnetic field inhomogeneity must be less than 1.8%.

V. ABSORPTION

Faraday rotator glasses typically have higher intrinsic absorption coefficients than normal optical glass. This is due to the strong optical transitions in the UV and blue spectral regions which provide the field dependent indices of refraction. A figure of merit that has been used for Faraday rotator materials[2] is V/α. Where V is the Verdet constant in min/Oe-cm and α is the intrinsic absorption coefficient in cm^{-1}. At 1.06 μ, α for EY-1 is less than 0.005 cm^{-1},[6] for Schott SF-6 it is ≈ 0.001 cm^{-1}.[3] The Schott glass is probably superior to the EY-1 glass using this figure of merit. However, the selection criteria for Faraday rotator glass that is to be used in high energy laser systems is maximum damage resistance and highest Verdet constant. Residual intrinsic absorption and temperature and wavelength stability are secondary considerations. EY-1 appears to be a very suitable material for high power optical rotators.

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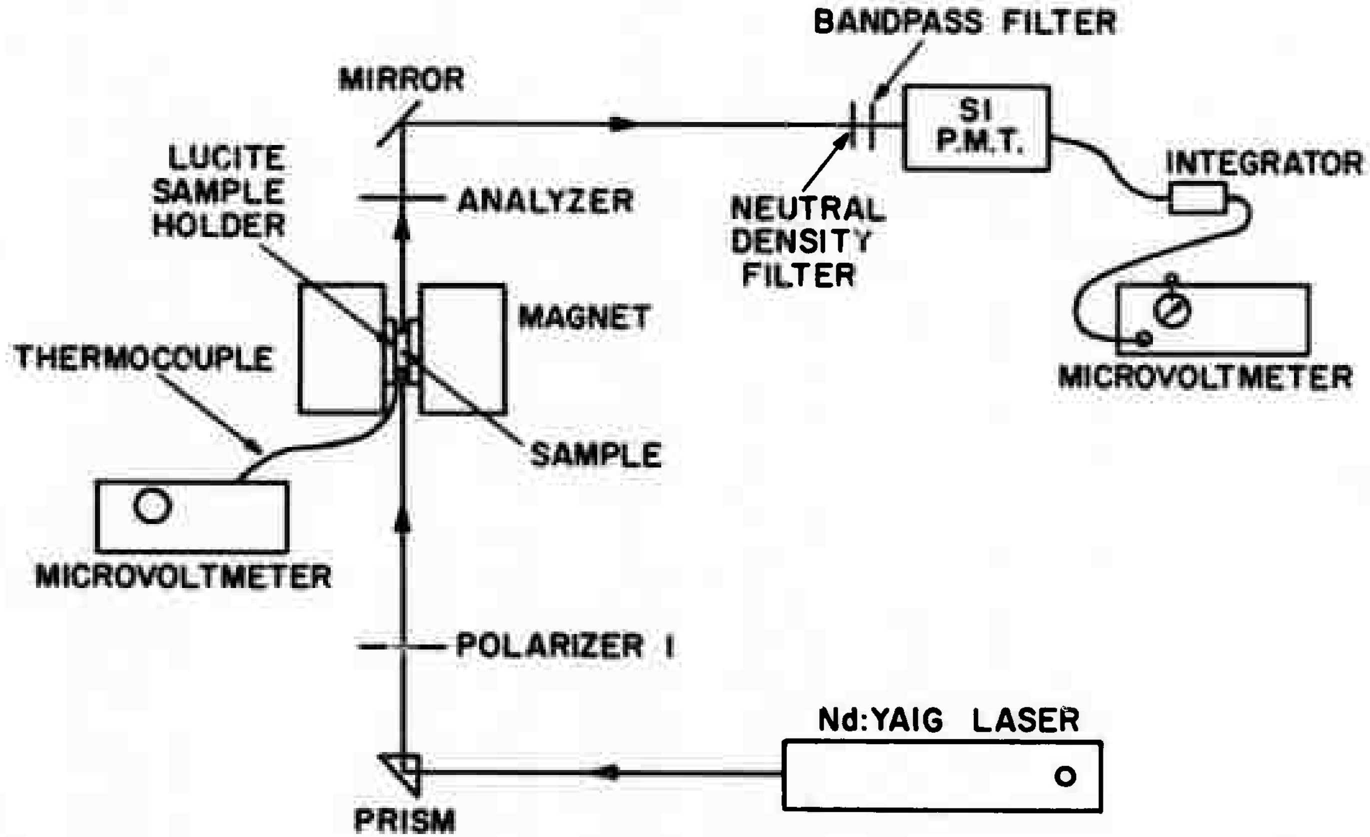

Fig. 1 – Experimental arrangement

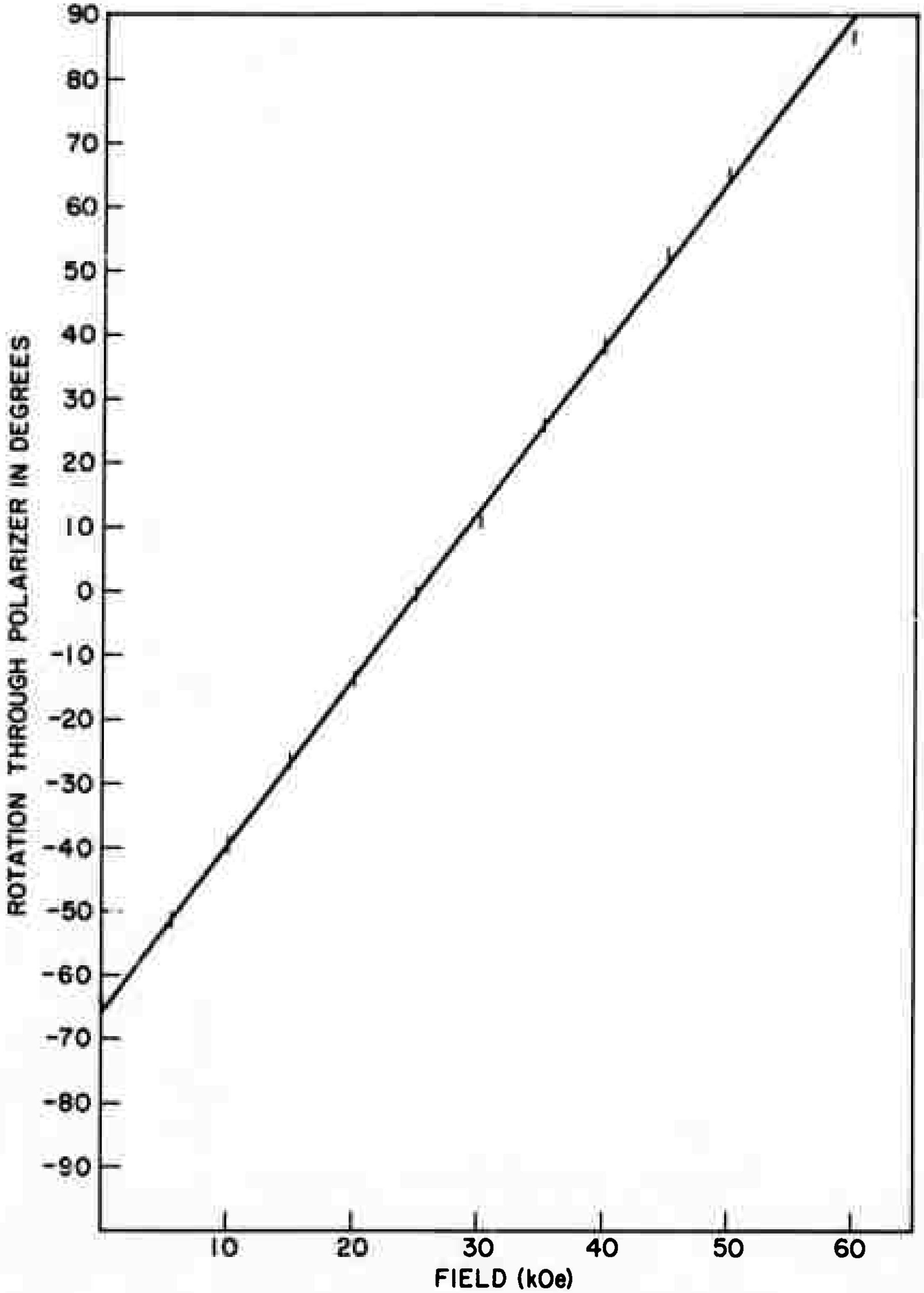

Fig. 2 - Rotation vs field at 19° C. Vertical bars show uncertainty in the data points.

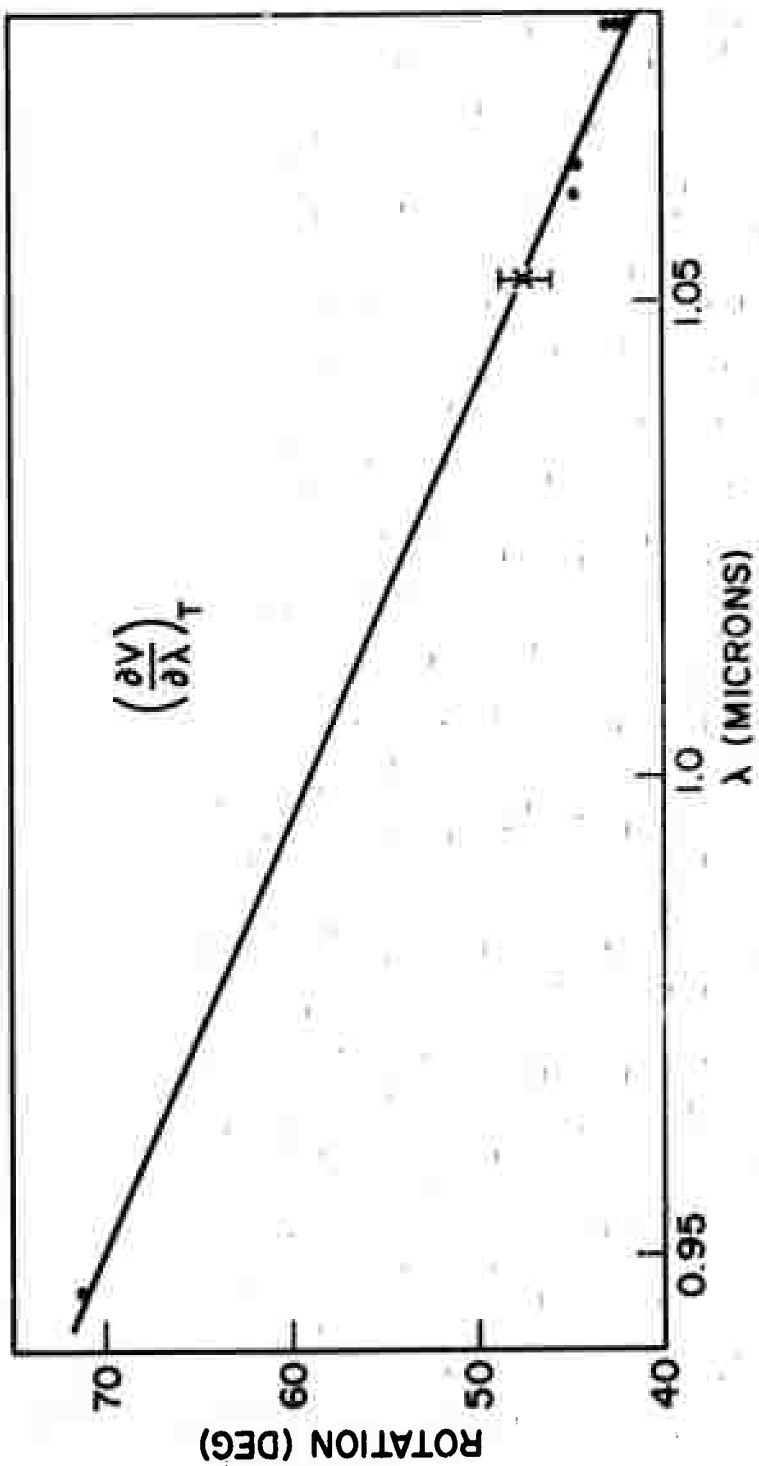

Fig. 3 - Rotation vs wavelength at constant temperature and field
H = 30 kOe and T = 12° C

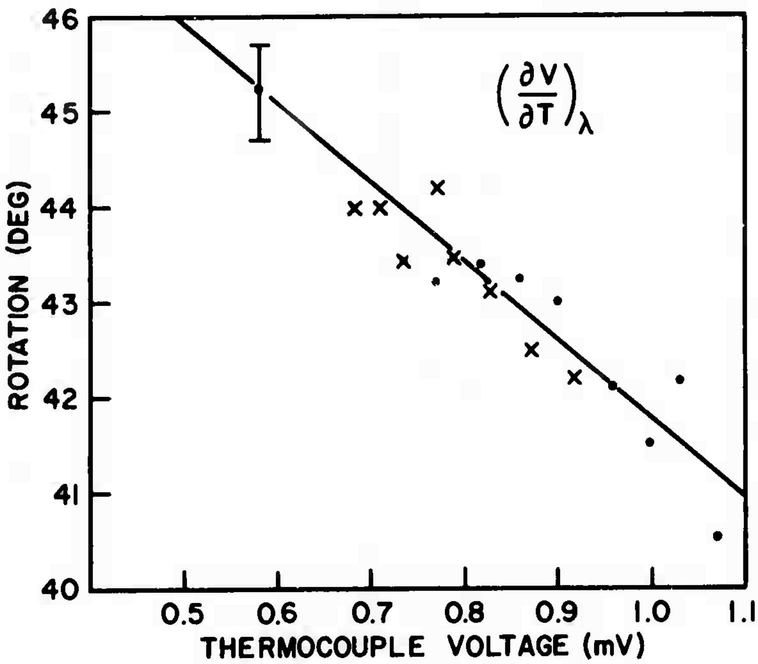

Fig. 4 - Rotation vs temperature at constant wavelength and field. H = 30 kOe and $\lambda = 1.064\ \mu$. Points and crosses are different data sets. The thermocouple response is 18.9° C/mVolt.

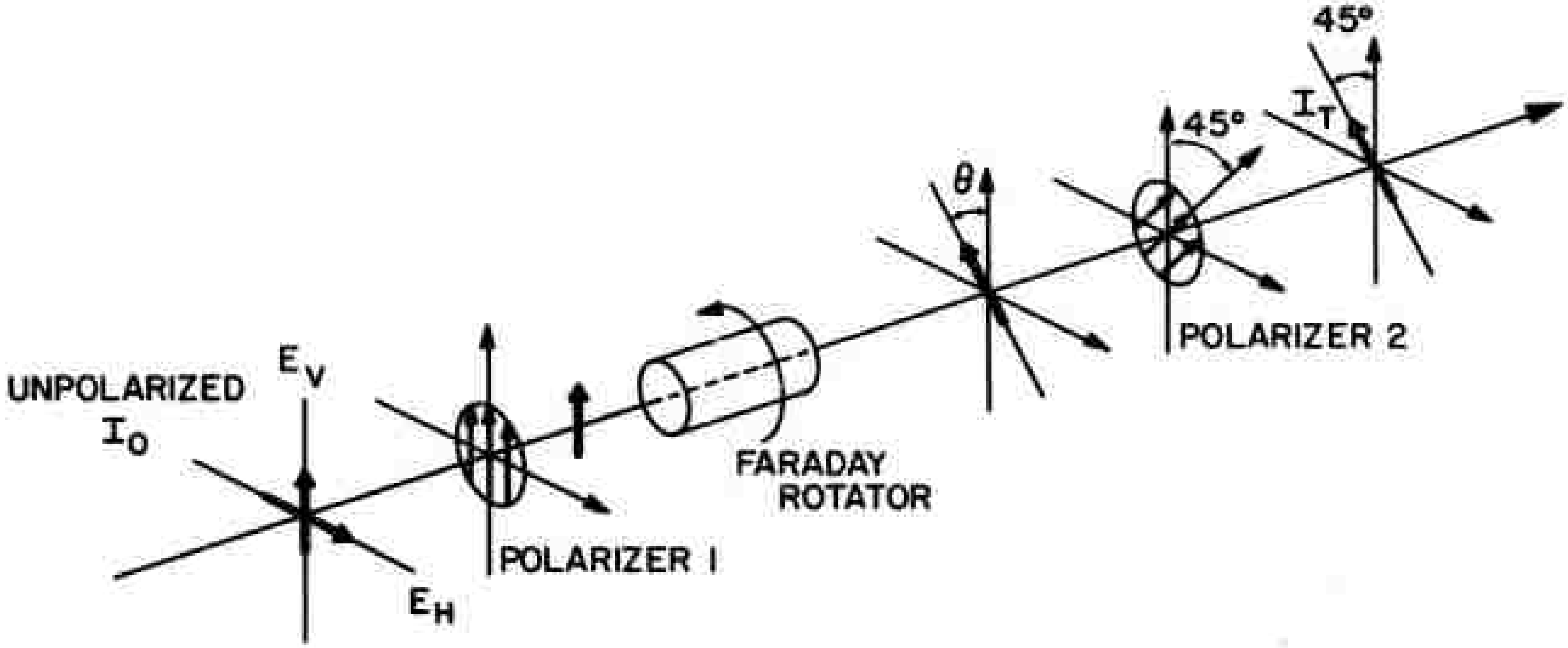

Fig. 5 – Schematic of Faraday rotator isolator system. Unpolarized light, I_o, is incident from the left. The transmitted light intensity, I_T, is equal to the extinction ratio, E, times I_o.